Insect-Pests in Dryland Agriculture and their Integrated Management

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1 Introduction

Insects are most adaptable to any condition and form of life. They constitute three-quarters of all the animals and are considered the most diverse of all living species on Earth. Apart from their natural oceanic habitat, they are found in deserts, mountains and also even in very harsh locations such as pools of crude petroleum (Imms 1964). Insects can have direct positive impacts on humans and the environment as predators or parasitoids of harmful pests, pollinators, decomposers or producers (honey or silk). However, only 1 % of all insects is considered pests (Vega and Kaya 2012) and is known to cause damage to crop plants, stored products and buildings, or act as vectors for animal and plant diseases, etc. About one-fifth of the world's total crop production is lost due to herbivorous insects. Several control measures have been developed to minimize the damage caused by insect pests, but the problem still prevails in several agroecosystems. One reason for this failure is the ability of insect pests to evolve new biotypes. They can, thus, adapt to overcome the effect of pesticides or bypass plant resistance, for instance, which further confounds the problem (Roush and McKenzie 1987).

In addition to the water and soil problems in dryland areas, insect pests pose a considerable threat to dryland cropping systems and production. Researchers estimate that food crops produced in the arid and semi-arid tropics are adversely

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affected by more than a thousand species of insect pests, fungi, viruses and weeds (http://exploreit.icrisat.org/page/pests_and_diseases/923). Certain pests flourish in dry environments while others prefer moist conditions. In any monoculture that is often practiced in dryland soils, once a pest settles in a field, serious damage can occur with frequent outbreaks of insect pests (Pimentel 2009). Many insect pests are common in dryland soils with life cycles of up to a year or more. Some dryland pests enter periods of dormancy, unlike wetland pests. Some insect pests such as armyworms, butterflies, locusts and grasshoppers have greater dispersal powers than most wetland insect pests, except for rice plant hoppers and leaf folders (Denno et al. 1991). In addition to insects, dryland pests include birds, rodents, wild pigs, monkeys, squirrels and even elephants and rhinoceroses (Grist and Lever 1969; Fujisaka et al. 1991).

Producers in different dryland regions (for example, USA) are regularly faced with aphid pressure in wheat fields, of which the most prevalent and detrimental are the greenbug (*Schizaphis graminum* R.) and Russian wheat aphid (*Diuraphis noxia* K.) (Kelsey and Mariger 2002; Giles et al. 2003; Momhinweg et al. 2006; Keenan et al. 2007a, b). The greenbug is considered the key pest of wheat in much of the dryland area in the United States due to its frequent occurrence and potential to cause severe crop damage. In the absence of management practices and natural enemies, greenbugs are capable of reproducing quickly in the warmer conditions of the Great Plains and subsequently reducing yields significantly, and sometimes exceeding economic injury levels (Kieckhefer and Kantack 1988; Webster 1995; Kindler et al. 2002, 2003; Giles et al. 2003). Aphids are chronic pests of peas and can transmit several viral diseases. Weevils can also damage peas and lentils in dryland areas.

Residual and other health-related problems regarding synthetic insecticides spur the development of biocontrol and other control practices for insect pests in dryland farming. Biotechnological approaches may provide opportunities to tailor biocontrol agents for the sustainable development of dryland cropping systems. In the long run, genetically-modified crops and integrated pest management (IPM) strategies may be the best options for IPM in dryland regions. This chapter is divided into sections with an emphasis on insect pests in dryland agriculture systems and their economic importance, followed by limitations and problems with management approaches. IPM approaches are discussed along with their advantages and disadvantages in dryland agriculture systems for enhancing productivity and food security.

2 Economic Importance of Insects in Dryland Agriculture Systems

Insects are part of the many components of an agroecosystem and are found in virtually every terrestrial, fresh-water environment. They are abundant on Earth and are involved in many biological processes. Contrary to popular belief, only 5000 insect species are considered harmful to crops, livestock or human beings of the roughly one million described species (Van Lenteren 2006). Insects benefit nature by regulating ecosystem services that are fundamental to the survival of humankind. For instance, insects play a significant role in plant reproduction, and about 70 % of the world's most productive crop species depend on pollinators to some extent, contributing an estimated €153 billion to the global economy and accounting for approximately 9 % of agricultural production (Teeb 2010). Pollinators play an important role in the food production process for several key fruit and certain vegetable crops, and consequently provide ecosystem services beneficial to human health, nutrition and, in turn, food security. In the case of dryland agriculture ecosystems, tight associations between dryland plants and pollinators are known; for example, Agava and its pollinator (Arizaga et al. 2000). The extent to which changes in dryland regions affect pollination services and the dependency of dryland plant species on pollination has not been fully explored. A wide range of plants benefit from pollinators, e.g. *Gloriosa minor* R. (Colchicaceae) is a species of dryland wildflower in Kenya that is pollinated exclusively by butterflies. It relies on pollinators for seed production and survival in arid environmental conditions (Martins 2014). Additionally, seeds of many dryland plant species can be disseminated by fruit-eating birds, often before or after their cross-desert seasonal migration, especially in the Mediterranean basin (Izhaki et al. 1991). Sometimes domestic and wild mammalian herbivores are involved in seed dispersal if seeds become attached to their fur or by consuming seeds and then defecating, which promotes dispersal and enhances the chance of germination, e.g., African acacia trees (Ward 2003). Livestock and other animals may also play a role in seed relocation from improved pasture lands to neighboring non-managed rangelands (CGIAR 1997). Therefore, the services of pollinators in dryland areas has a significant impact; however, changing conditions and cropping biodiversity require more attention for the future of the pollinator's contribution in dryland areas.

In addition to pollination, insects play an equally vital role in waste biodegradation. This service supports soil development and primary production through the breakdown of dead plant parts, enriching the soil with organic matter until it is fit to be consumed by fungi and bacteria and regenerating mineral plant nutrients (Shapiro et al. 2005). A wide range of insects, including beetle larvae, flies, ants and termites, clean up dead plant matter which breaks down the organic matter and nutrients of dead organisms to then be readily available in the soil for plants. Unlike non-dryland areas, where insects and other soil microorganisms are major players in nutrient cycling, invertebrate macro-decomposers play a significant role in dryland areas, and their role increases with aridity. In dry and warmer parts, many termite species contain host nitrogen-fixing organisms in their gut, so they can increase the nitrogen content of soil to benefit crops (Cunningham et al. 2010). Some populations, such as microbes and fungi, decline with aridity due to their stringent moisture dependence. Similarly, the role of large herbivores for nutrient cycling is limited due to the lack of drinking water in arid and hyper-arid areas. However, some macro-decomposers, such as termites, darkling beetles (Tenebrionidae) and other soil dwellers, are less moisture sensitive so become vital for nutrient cycling in dryland areas. These organisms are important in litter preparation for microbial activity and increase the soil infiltration capacity which acts as a key to enhancing crop production (Shapiro et al. 2005).

When dryland areas are used as rangelands, most of the primary production takes place with livestock rather than macro-decomposers. However, livestock may gradually deplete the nitrogen reserves and further exacerbate the nutrient limitations for primary production (Ayal et al. 2005). This depletion may be partially mitigated by biological nitrogen fixation and by urea deposition in the soil (Shachak and Lovett 1998). Conversely, when dryland areas are used for crop production, some cultural practices such as tillage and the excessive use of chemicals to manage insect pests can reduce the role of soil-dwelling macro-decomposers. This, together with the low root biomass of annual crops, can impair nutrient cycling and decrease soil organic carbon and its associated nutrients (Shapiro et al. 2005).

Moreover, natural enemies—insect predators and parasitoids—attack and feed on other insect pests to keep them under economic threshold levels. Thus, they can be manipulated in pest management programs to avoid the use of toxic chemicals (Table 1). Natural enemies help to prevent the outbreak of pest populations and contribute to a type of pest regulation referred to as natural biological control. Natural enemies are responsible for 33 % of natural pest control in cultivated systems (Getanjaly et al. 2015). Natural enemies belong to about 20 insect orders and are characterized as free-living, mobile, larger than their prey, and able to consume several prey throughout their life cycle (DeBach and Rosen 1991). Whereas parasitoids are mainly belonging to the Hymenoptera and Diptera orders with a more specialized host range than predators (Strand and Obrycki 1996). Free-living adult parasitoids parasitize different life stages of their host (i.e. egg, larva, pupa or adult) depending on the parasitoid species. Parasitoids can lay their egg (solitary) or several eggs (gregarious) on or within their host; after hatching, the immature parasitoid(s) feed on their host to complete development by consuming the host and emerging as a free-living adult (DeBach and Rosen 1991). Dryland crops like chickpea (*Cicer arietinum* L.) and pigeon pea (*Cajanus cajan* L.), for example, stand to benefit if natural enemies can be maintained in farmers' fields. However, both species produce trichomes or small hairs that act as a natural defense against predators which can reduce the effectiveness of natural enemies. To increase the effectiveness of these natural enemies, non-trichome-producing genotypes have been developed. Unlike non-dryland environments, hot and dry conditions in dryland areas affect the bionomics and efficiency of natural enemies. For example, the survival of the egg parasitoid, *Trichogramma carverae* O. (Scott et al. 1997) and *Campoletis chlorideae* U. on chickpea pod borer (*Helicoverpa armigera* H.) declines when exposed to abrupt high-temperature changes (Dhillon and Sharma 2009). Similarly, the host searching ability of egg parasitoid *T. carverae* decreases at higher temperatures (Thomson et al. 2001). Reduced fecundity of egg parasitoids, *T. pretiosum* R. and *Trichogrammatoidea bactrae* N. has been recorded at temperatures prevailing above threshold levels (Naranjo 1993). Hot and dry weather conditions in dryland areas reduce parasitism e.g. poor parasitization of egg parasitoid, *Trichogramma* on European corn borer (*Ostrinia nubulalis* H.) affects the natural/biological control of pests in arid areas (Cagan et al. 1998).

Table 1 The natural enemies of important insect pests of dryland crops

Predator/ Parasitoid	Group	Beneficial insect or invertebrate	Target host/prey
Predators	Beetles	Ladybirds (Coccinellidae), red and blue beetles (*Dicranolaius bellulus* G.), green carab beetles (*Calosoma schayeri* E.), green soldier beetles (*Chauliognathus pulchellus* M.)	Aphids, mites, thrips, mealybugs, moth eggs including *Heliothis* spp. and larvae
	Bugs	Assassin bugs (Reduviidae), bigeyed bugs (*Geocoris lubra* K.), brown smudge bugs (*Deraeocoris signatus* D.), damsel bugs (*Nabis kingbergii* R.), glossy shield bug (*Cermatulus nasalis* W.), pirate bug (*Orius spp.*), apple dimple bug (*Campylomma liebknectic* G.), spined predatory shield bug (*Oechalia schellenbergii* G.), broken backed bug (*Taylorilygus pallidulus* B.)	Aphids, diamondback moth, eggs and larvae of *Heliothis* spp., cutworms (*Spodoptera litura* F.), false loopers
	Flies	Hoverfly larvae (Syrphidae)	Aphids
	Mites	Predatory mites from different families (Anystidae, Bdellidae, Erythraeida, Parasitidae and Cunaxidae)	Blue oat mite, lucerne flea, red legged earth mite
	Lacewings	Green lacewing (*Mallada signatus* S.), brown lacewing (*Micromus tasmaniae* W.)	Aphids, moth larvae and eggs, whitefly, thrips, mites and mealybugs
	Spiders	Variety of species including wolf spiders, nights talking spiders, orb weavers, tangle web spiders, flower spiders, jumping spiders and lynx spiders	Predators or a range of insect pests
Parasitoids	Sucking insect parasitoids	*Trioxys complanatus* Q., *Aphidius ervi* H., *Lysiphlebus testaceipes* C., *Aphidius colemani* V.	Aphids
		Eretmocerus spp. and *Encarsia* spp. including *Encarsia Formosa* G.	Whitefly
	Chewing insect parasitoids	Hymenoptera: Numerous parasitic wasps including banded caterpillar parasite (*Ichneumon promissorius* E.), two-toned caterpillar parasite (*Heteropelma scaposum* M.) (Ichneumonidae), *Microplitis demolitor* W., *Cotesia* spp. (Braconidae)	*Heliothis* and other moth larvae
		Sorghum midge parasites (*Eupelmus australiensis* G., *Aprostocetus diplosidis* C., *Tetrastichus* spp.)	Sorghum midge
		Tachinid flies	*Heliothis*, looper, armyworm, grasshopper and other larvae
	Egg parasitoids	Hymenoptera: *Trichogramma* (Trichogrammatidae) and *Telenomus* (Scelionidae) egg parasitoids	*Helicoverpa* and other Lepidopteran insect pests
		Trissolcus basalis W.	Green vegetable bug

Source: Getanjaly et al. (2015), Dixon (2000), and Eggleton and Belshaw (1992)

There are predators of pests that can be affected by dry conditions. Some fungi require humidity to survive, so are less effective during droughts, whereas others perform better in dry conditions. The parasitic wasp lays its eggs in the cereal leaf beetle's pupa, a life-cycle stage between the larva and the adult. After hatching, the wasp larvae eat the pupa's non-vital tissues and finally kill it while emerging from its body. Beetle pupae normally cover themselves in faeces; Sanford Eigenbrode (an entomologist at the University of Idaho in Moscow) suspects that this faecal shield acts as a barrier to keep the wasp at bay (ref?). However, producing faeces requires water and Eigenbrode thinks that in extremely dry conditions, beetle larvae are unable to deploy their shields quickly enough to prevent predation from parasitic wasps (Maxmen 2013).

A better understanding of the beneficial insects in dryland systems will make their conservation easier and their role for pest management. Fields shared by many beneficial insects will positively affect crop yields, so farmers need to be made aware of the beneficial insects in dryland agriculture and decisions should be made carefully as to how to manage insect pests.

3 Insect-Pests in Dryland Agriculture Systems

Insect pests and diseases are serious constraints to crop production and human consumption of these crops is at risk due to their incidence, both in dryland and non-dryland ecosystems. With few exceptions, insect pests in the arid zone do not differ greatly from those encountered in temperate and humid regions; however, the list of major insect pests in dryland crops is provided in Table 2. Dryland areas tend to be hot and insects generally thrive in warmer conditions. As the temperature rises, the excessive heat accelerates an insect's development and provides a favorable thermal environment for growth and development of plant-feeding insects. They eat more, mate more and produce more young (Maxmen 2013). Dry conditions also make plants more attractive and nutritious to insect pests (increased larval weight, survival and reproduction). Water-deficient plants are more susceptible to insects because the production of secondary metabolites or defensive compounds declines under water stress which increases the susceptibility to attack. Unlike non-dryland environments, dry conditions increase insect detoxification systems and insects feeding on water-stressed plants are capable of breaking down certain plant allelochemicals or defensive compounds that would normally have a negative effect on them. Studies suggest that some herbivorous insects specifically target water-stressed plants; however, the effect of drought stress varies depending on the feeding behaviors of insect pests. Insects with piercing-sucking mouthparts (aphids, whiteflies, scales and plant bugs) typically benefit more from dry conditions than those with chewing mouthparts (beetles, caterpillars and sawflies). Water-stressed plants are often susceptible to wood-boring insects such as bronze birch borer (*Agrilus anxius* G.), two lined chestnut borer (*Agrilus bilineatus* W.) and bark beetles due to reduced production of certain compounds (oleoresin) which act to deter

Table 2 Insect pests of dryland crops, host crops and their mode of damage

Common name	Scientific name	Order: Family	Host crop	Mode of damage	Sources
Termites	*Microtermes mycophagous* D.	Isoptera: Termitidae	Wheat, sorghum	Many species are crops with damage caused to stems and roots of seedlings and mature plants which can result in significant yield losses.	Perry and Perry (1989)
Sugarcane beetle	*Holotrichia consanguinea* B.	Coeloptera: Melolonthinae	Pearl millet	Damage soon after sowing and sometimes near maturity. Damaged plants dry up completely and are easily pulled out. Plants damaged at later stages give rise to white ears.	
Locusts	*Chortoicetes terminifera* W.	Orthoptera: Acrididae	Pearl millet, sorghum, barley, oats, etc.	Damage most green plants. Eat a wide range of food and each one eats its weight in food daily.	Maxmen (2013)
Grasshoppers	*Chrotogonus trachypterus* B.	Orthoptera: Pyrgomorphidae	Pasture, grains, forage, vegetables	General feeders on grasses and weeds and often move to cultivated crops. Crop damage is likely to be greatest in years when dry weather accompanies high populations.	Perry and Perry (1989)
Aphids	*Rhopalosiphum maidis* F. *R. padi* L.	Hemiptera: Aphididae	Wheat, maize, barley, forage legumes, sunflower, oilseeds, fruit trees, etc.	Sucking insect pest. Most destructive pest on cultivated plants causing yellowing, mottled leaves, stunted growth, curled leaves, browning, low yields and even death in plants.	Asin and Pons (2001), Irshad (2001) and Taheri et al. (2010)

(continued)

Table 2 (continued)

Common name	Scientific name	Order: Family	Host crop	Mode of damage	Sources
Weevils	*Myllocerus discolor* B.	Coleoptera: Curculionidae	Peas, lentils, pearl millet, sunflower, sorghum, etc.	Feed on plants in the larval stage and as adults. Very destructive to crops. One of the most destructive weevils is the cotton boll weevil.	Butani (1979) and Hill (1987)
Moths	*Achaea janata* L. *Heliocheilus albipunctella* J.	Lepidoptera: Noctuidae	Castor, pearl millet, etc.	Most lepidopterans are moths. Very destructive to crops at larval stages.	Perry and Perry (1989)
Hessian fly	*Mayetiola destructor* S.	Diptera: Cecidomyiidae	Wheat, barley, etc.	Maggots hatch from eggs, and crawl to the crown of seedlings (just above the roots) and feed on plant juices after injecting their unique saliva. Feeding by one larva can permanently stunt plant growth.	Anonymous (1971)
Shoot fly	*Atherigona soccata* R.	Diptera: Muscidae	Sorghum, pearl millet, maize etc.	The larva (maggot) feed on the growing point of the shoot of the seedling and cause "dead heart".	Perry and Perry (1989)
Wheat stem sawfly	*Cephus cinctus* N.	Hymenoptera: Cephidae	Wheat, other cereals	The larvae begin feeding near the oviposition site, eventually feeding up and down the stem, chewing through nodes.	Morrill (1995)

Sugarcane leafhopper	*Pyrilla perpusilla* W.	Hemiptera; Fulgoridae	Sorghum, pearl millet, sugarcane, etc.	Sucks phloem sap from leaves and excretes honeydew onto foliage, leading to fungal diseases. This direct and indirect damage affects sugar yield and quality.	Perry and Perry (1989)
Acacia white fly	*Tetraleurodes acacia* Q.	Hemiptera: Aleyrodidae	Acacia	Feeds by tapping into the phloem of plants, injecting toxic saliva and decreasing the overall turgor pressure of plants.	John et al. (2007) and Srinivasa (2000)
Thrips	*Scirtothrips aurantii* F.	Thysanoptera; Thripidae	Eucalyptus, citrus, etc.	Immature and adult thrips prefer to feed on young leaves in the inner neck of plants and cause severe damage by sucking the cell sap.	Mirab-Balou et al. (2011) and Loomans and Van Lenteren (1995)

feeding. For instance, the mountain pine beetle (*Dendroctonus ponderosae* H.) killed about 750,000 hectares of trees in 2010–2011 in the western United States in an infestation thought to be fueled in part by dry conditions (Chapman et al. 2012). Pine trees normally secrete a sticky resin which suffocates beetles burrowing underneath the bark, but water-stressed trees are unable to produce enough sap. Beetles finding such trees emit chemical signals (pheromones) that attract other beetles. The resulting mass predation further deteriorates the tree and the beetle population multiplies. Additionally, water-stressed plants emit volatile chemicals, e.g. ethanol and alpha pinene that attract these types of insects. Wood-boring insects use these chemical cues which facilitate them to find these plants whose natural defenses are already compromised due to water deficiency. Moreover, the lack of moisture in the upper tree canopy may result in cambial and phloem tissue degradation which is attractive to wood-boring female insects (bronze birch borer) for egg laying. Similarly, bark beetles colonize and weaken the defenses of their target plants. Dry conditions also encourage the development of two spotted spider mite (*Tetranychus urticae* K.) populations as these mites tend to feed more under dry conditions. According to Claudio Gratton (an entomologist at the University of Wisconsin-Madison), the relationship between insect populations and dry conditions is not consistent because sometimes there are more insects and sometimes less (Maxmen 2013). One explanation for this variation might be that insects can respond positively to dry conditions for a period. Eventually, they suffer as the plants they feed on weaken or deteriorate. For example, aphids can flourish during a short dry spell as plant nutrients become more concentrated. However, these benefits cease during prolonged dry seasons due to a drop in fluid pressure within the phloem of water-stressed plants (Huberty and Denno 2004). The dryland environments are associated with long dry seasons, and both insect pests and farmers spring into action upon the resumption of rainfall. Thus, the insects start damaging crops at the seedling stage because aestivation in seedling maggots and white grubs is broken by early heavy rains (Litsinger et al. 2002).

4 Limitations and Problems of Insect-Pest Management Approaches

Integrated management is not a panacea for every insect pest problem. Certain limitations are associated with any insect control program, and IMP is not an exception. With about one million described species, insects are dominant creatures in the world (Vega and Kaya 2012) with their short life cycles, high reproduction rates, variability, and adaptation to the environment. Therefore, every cultivated crop can be attacked by a complex of insect pest species. Modern agriculture practices (monoculture, high rate of plant fertilization and indiscriminate chemical control application, etc.) have decimated natural enemies of insects which formerly played an important role in maintaining insect pest populations at the general equilibrium position.

4.1 Insect Adaptations in Dryland

Insects have adapted to survive in dryland conditions through morphological, physiological, behavioral and ecological modifications (Cloudsley-Thompson 1975). Morphological adaptations of insects in arid environments include the creation of a boundary layer of hairs or scales to reduce the absorption of heat from the environment, and the resistance to water loss thorough spiracles. Some adaptations include modifications of body forms and legs for burrowing and running on hot surfaces. Body colors vary from ochre, brown, sandy grey or other colors, but insects are predominantly black. These colors characterize those insects that are relished by natural enemies. Adaptations to protect the young in harsh desert conditions include the construction of egg pods, larval cases and pupal cocoons. The behavioral adaptations of insects force them to confine themselves to favorable microhabitats. They feed and mate during those hours or seasons when conditions are favorable (Arnon 1992). Some insects in arid regions spend most of their time underground or under stones where the conditions are favorable compared to the open environment. There are many species in arid regions which remain dormant (similar to ephemeral plants) for extensive periods of dryness, heat and hot winds. This may occur in insects of cultivated plants in dryland conditions. For example, *Sesamia* larvae of dryland sorghum become dormant within stalks during hot summer. In contrast, the dormancy of pests occurs much later in irrigated sorghum. In some cases, the eggs remain dormant until sufficient rainfall occurs, e.g., Desert locust (*Schistocerca gregaria* F.). Many carnivorous insects in the desert store food for their progeny.

Physiological adaptations of arid-region insects include tolerance of high temperature, low respiration, and water uptake from the atmosphere, water conservation for metabolic activities, facultative hyperthermia, and resistance to desiccation (Cloudsley-Thompson 1975). These characteristics are not present in all insects, but many have multiple adaptations which help them to survive under adverse conditions. Some insects are so adapted to arid and semi-arid conditions that humid conditions can be harmful, e.g., chinch bug (*Blissus leucopterus* S.) and pale western cutworm (*Porosagrotis orthogonia* Morr.) (Arnon 1992). The fluctuation in temperature affects the life cycle of insects and, if not excessive, can accelerate developmental cycles. As a result, insects have more generations per year. In dryland regions, the rainy season is short but vital for insect breeding while adverse biological and physical conditions cause high mortality in insect populations. Therefore, irrigation in arid regions causes profound changes both in vegetation (cultivated and spontaneous) and insect populations. Irrigation can extend the favorable period for breeding and reduce the unfavorable conditions responsible for checking the increase in the insect population. In the absence of any natural control, epidemics may occur.

4.2 Drylands as Reservoirs for Potential Insect Pests

Indeed, many insect populations are not able to maintain their populations under adverse conditions in dryland areas. They can, however, serve as a reservoir for insect pests which spread to damaged, adjacent irrigated regions. Mckinney (1939) reported that the introduction of irrigation in the isolated Salt River Valley of Arizona increased the abundance and adaptation of certain insect species in cultivated crops that originally subsisted on native wild vegetation. Many moths migrate at night from their arid breeding habitats to irrigated or higher rainfall areas during the dry season, e.g., cotton leafworm (*Alabama argillacea* H.) and black cutworm (*Agrotis ipsilon* H.). The beet leaf hopper (*Circulifer tenellus* B.) overwinters in desert areas of southwestern United States which usually receives winter rainfall. In late spring, the beet leaf hopper migrates to newly-sown irrigated beet crops and causes infection with beet curly-top virus (Siegel and Hari 1980). Similarly, the desert locust is a typical example of desert region insects which become a major pest of cultivated crops far from their native area. They require moist sand for egg laying, and abundant green and tender food for their young. A locust can eat ten times their weight in vegetation. Land development schemes based on irrigation may provide favorable breeding grounds for locusts, making locusts even more dangerous than in the past. In addition to locusts, other insects which feed on the native vegetation of arid and semi-arid regions have become major pests of cultivated crops; for example, wheat thrips (*Haplothrips tritici* K.), sorghum midge (*Contarinia sorghicola* C.), cotton boll weevil (*Anthonomus grandis* B.) and beet leafhopper (*Circulifer tenellus* B.) (Uvarov 1962).

4.3 Injudicious Chemical Use and Insect Resistance

Approximately 45 % of the worldwide consumption of pesticides is in Europe, with 25 % in the USA and 30 % in the rest of the world (De et al. 2014). Estimated crop losses are between 10 and 30 % in developed nations but as high as 75 % in developing countries (Ohayo-Mitoko et al. 1997). Thus, chemical pesticide use is common for increasing crop productivity because pesticides protect crops by eliminating, inhibiting or controlling pests. Pesticides may affect plant development, prevent or kill competitive vegetation, or aid in the management of final products. But many studies have shown that high pesticide use may pose a serious threat to soil and water quality (Arias-Estévez et al. 2008), human health (Athukorala et al. 2012; Nawaz et al. 2014), food safety (Liu et al. 1995), aquatic species (Skevas et al. 2013) and beneficial insects (Mullen et al. 1997). Insecticide resistance is a major constraint in the management of insect pests of agricultural and public health importance (Khan et al. 2011). Cotton is considered a major crop in dryland agriculture, with reported insecticide resistance in major insect pests such as *Helicoverpa armigera* H., *Pectinophora gossypiella* S., *Earias vittella* F., *Spodoptera litura* F. and

Bemisia tabaci G. (Jan et al. 2015; Kranthi et al. 2002; Martin et al. 2000). Similarly, insecticide resistance has been observed in other major pests of dryland agricultural crops, including olive fruit fly (*Bactrocera oleae* R.; Vontas et al. 2001), melon fruit fly (*Bactrocera cucurbitae* C.; Vontas et al. 2011), oriental fruit fly (*Bactrocera dorsalis* H.; Hsu and Feng 2006), codling moth (*Cydia pomonella* L.; Reyes et al. 2015, Reyes et al. 2007).

4.4 Climate Change and Insect Pest Control

Climate change is occurring; the last decade of the twentieth century and the first decade of the twenty-first century have been the warmest periods on record. The global mean surface temperature rose approximately 0.6 ± 0.2 °C during the twentieth century, and climatic models have predicted an average increase in global temperature of 1.8–4 °C over the next 100 years (Collins et al. 2007; Johansen 2002; Karl and Trenbeth 2003). This is the largest increase in temperature in any century in the past 1000 years (Houghton et al. 2001). If temperatures rise about 2 °C in the next 100 years, then the negative effects of global warming would begin to extend worldwide (Griggs and Noguer 2002). Insects are poikilothermic (cold-blooded) organisms, i.e. their body temperatures vary with the surrounding temperatures. They are strongly influenced by changing climatic and weather conditions. Their rate of development, reproduction, migration, adaptation and distribution is directly affected by temperature, humidity, precipitation, wind speed, etc. In addition, host plants, natural enemies and interspecific interactions with other insects indirectly affect insects. Thus, climate change poses a threat to the control of insect pests. Similarly, increasing levels of greenhouse gases in the atmosphere may significantly impact agricultural insect pests. Consequently, existing pests at low densities may spread on a broad spectrum and reach damaging population densities (Bale et al. 2002; Porter et al. 1991).

Population dynamics of insects deal with factors affecting population densities. The rise in temperature positively affects the development of certain pests until it exceeds the optimal requirements of the species. For example, bark beetles profit from accelerated development rates with early completion of life cycles to produce more generations within a season. A rise in temperature above favorable conditions may decrease growth rates and fecundity, and increase mortality rates in many species (Jönsson et al. 2009; Rouault et al. 2006). Many species require a dormancy phase to complete their life cycle. Increased temperatures may benefit those species which actively feed during winter but may have a negative impact on those species which require low temperature for diapause (Bale et al. 2002). Migration and dispersal are essential parameters in the phenology of herbivorous insects for host finding, mating, colonization and brood establishment. Temperature requirements have been described for different phases of flight activities. For instance, black bean aphid (*Aphis fabae* S.) requires 6.5 °C for wing beating, 13 °C for horizontal flight, 15 °C for sustained upward flight and 17 °C for take-off (Cockbain 1961).

Temperature directly affects the survival rate of insects. For example, survival of the brown plant hopper (*Nilapavata lugens* S.) remains unchanged between 25 and 35 °C but significantly declines at 40 °C. The oviposition efficiency of female brown plant hopper (BPH) was relatively higher at a higher temperature (35 and 40 °C) while egg survival declined at 35 °C. The pre-oviposition period also shortened at high temperature (Heong et al. 1995). The viability of eggs and required degree days for hatching of *Helicoverpa ammigera* reduced with increasing temperature (Dhillon and Sharma 2007). Similarly, the effect of temperature on growth rate, voltinism (number of generations per year), and species distribution of various insects has been described (Chakravarthy and Gautam 2002; Régnière et al. 2012; Tobin et al. 2008).

In addition to temperature effects on insects, changes in precipitation and rising CO_2 levels also affect insect life cycles. A number of insects are sensitive to precipitation and heavy rains can kill or remove them from crops. Increased summer rainfall and drought conditions promoted growth in the upper soil of a wireworm population (Staley et al. 2007). The effect of rising levels of CO_2 on levels of herbivory in soybean was tested using FACE (free air gas concentration enrichment) technology. A soybean crop grown in an elevated CO_2 atmosphere had 57 % more damage from insects compared with those grown in the natural atmosphere (Hamilton et al. 2005). This evidence shows that climate change in different agro-ecosystems and ecological zones might affect the population dynamics of insect pests. The prediction of climate change impacts on insects is somewhat uncertain and may be positive for certain insects and negative for others. The increase in insect outbreaks will increase the use of insecticides which is likely to have a negative impact on the environment. Therefore, the best economic strategy for farmers is to practice integrated pest management.

4.5 Lack of Conservation of Natural Enemies

Paul DeBach defines conservation biological control as "manipulation of the environment to favor natural enemies, either by removing or mitigating adverse factors or by providing lacking requisites" (Naranjo 2001). Natural enemies can play a pivotal role in the management of insect pests and is often credited with being the oldest form of biological control. Conservation of endemic natural enemies has been less successful in field crops and has received little attention as a method of arthropod pest suppression compared with classical and augmentation biological control (Landis et al. 2000).

4.5.1 Insecticides

The factors affecting the conservation natural enemies are frequent application of pesticides, periodic disruption of the soil structure by heavy tillage, frequent planting and rotation, removal of crop residues, and the destruction of plant structures with harvesting. The production of monoculture crops (often practiced in dryland systems) often lacks the alternative food sources—flowers for nectar and pollen as well as shelter—which may natural enemies need. It is evident from both laboratory and field studies that the most significant disrupting factor for the biological control of arthropod pests is the use of toxic insecticides. These insecticides cause species and stage (egg, larvae, pupa and adult) specific toxicity to the predators and parasitoids of different insects (Croft 1990; Gerling and Sinai 1994; Hoseini et al. 2012; Simmons and Jackson 2000; Smith et al. 1999). Some selective insecticides for pest management are available but disruption of biocontrol agents is still likely in some agricultural systems. The presence of multiple key pests is reason to use broad-spectrum insecticides due to the lack of available selective control measures. Additionally, economic consideration is important due to the high cost of IGRs (insect growth regulators); some areas may be forced to opt for cheaper but more destructive pesticides.

4.5.2 Other Factors

Aside from insecticides, other factors contribute to biological control disruption but have received little attention. Intraguild predation (IP) is well known in many cropping systems. The aphelinid heteronomous hyperparasitoids attacking whitefly is possibly the best-known example of IP. They produce males as hyperparasitoids and females as primary parasitoids. This type of behavior can be disruptive to biological control (Mills and Gutierrez 1996). Therefore, IP is possibly common due to the diversity of natural enemies attacking large numbers of insect pests and may play an integral part in determining the role of natural enemy species in affected crops. Characteristics of the host plant, degree of leaf glossiness or levels of nitrogen may affect the biology and behavior of natural enemies (Bentz et al. 1996; Jackson et al. 2000; Wilson and George 1986). These factors highlight the challenges faced in the integration of biological control into economically-sustainable pest management strategies for multiple pest management systems.

In many biological control systems, the efficacy of natural enemies—imported or mass reared—is likely to depend on conservation measures and the suitability of the environment in which they are released. The conservation of natural enemies can occur in dryland agriculture systems by focusing on three overlapping components: (i) survey and identification of extant natural enemies, (ii) elucidation of constraints and manipulation of factors enhancing the abundance of natural enemies, and (iii) evaluation of the biological control efficacy of released natural enemies in that particular system (Fig. 1).

4.6 Impact of Genetically Modified Crops on Insect

Plant breeding history reveals the use of new technologies for improving crop cultivars by manipulating chromosome number, chemical and radiation treatment to induce mutations, and developing addition/substitution lines as well as cell and

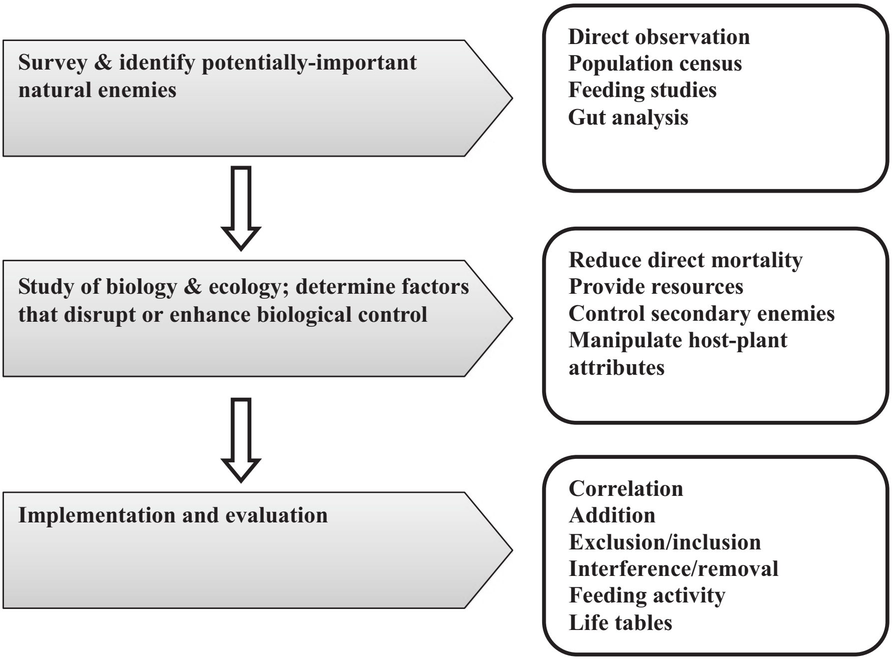

Fig. 1 Components and approaches of conservation biological control

tissue cultures. All have contributed to improved yields, developed resistance to specific diseases and pests, environmental adaptations and improved quality demanded by the food industry and consumers. Cell culture and molecular biology advances have culminated in the genetic modification of crops. Currently, genetic modification of plants is a powerful, widespread but controversial application of biotechnology (Conner et al. 2003; Mendelsohn et al. 2003; Sanahuja et al. 2011). GM crops have reduced, and continue to reduce herbicide, insecticide and overall pesticide use (Benbrook 2012). Despite the potential benefits, environmental and food safety concerns have been raised about GM crops. It is feared that GM crops will harm the human population with undesired impacts on the environment. Concerns regarding the introduction of GM crops into the environment include the effects on biodiversity, becoming agricultural weeds, direct and indirect effects on non-target organisms, and food safety (Conner et al. 2003).

4.6.1 Impact on Insect Pests

The area under *Bacillus thurengiensis* (Bt) crops increased from 1.1 million to 66 million hectares from 1996 to 2011 with a cumulative total of more than 420 million hectares. Insects have a remarkable ability to adapt insecticides and other control tactics. The development of resistance can reduce the effectiveness of insecticidal Bt proteins in transgenic plants. Therefore, the main threat to the continued success of Bt crops is the evolution of resistance in pests. Some reviews have addressed insect pest resistance in GM crops (Carrière et al. 2010; Pardo-Lopez et al. 2013; Tabashnik 1994). Several studies have compared the field outcomes for resistance to Bt crops but with limited sample sizes for both field outcomes and other factors predicted to affect resistance (Carrière et al. 2010; Tabashnik 2008; Tabashnik et al. 2009). A 2012 review summarized pest resistance to Bt crops by analyzing field monitoring data for resistance from 77 different studies, and reported resistance for some populations of 5 of 13 major pest species (lepidopteran and coleopteran) examined when compared with resistant populations of only one pest species in 2005. The number of major pest species with field-evolved resistance and reduced transgenic crop efficacy increased from one to five (three Bt corn and two Bt cotton) from 2005–2010 (Tabashnik et al. 2013). Another study revealed that the insect resistance percentage to GM crops increased from 0.93 % in 2010 to 5.5 % in 2013. Therefore, pest resistance management is necessary to attain the full benefit of GM crops to minimize food security issues. The factors responsible for delaying resistance include the use of abundant non-Bt refuge crops, recessive inheritance of resistance, the low initial frequency of resistant alleles, and separate deployment of two-toxin Bt crops from one-toxin Bt crops. It was predicted that without natural refuge crops, the percentage of resistant insects to GM crops would exceed 98 % in 2013 but would increase by only 1.1 % if natural refuges were as effective as non-Bt cotton refuges. Similarly, the percentage of resistant insects increased from 37 % in 2010 to 84 % in 2013 with the non-recessive inheritance of resistance (Jin et al. 2015; Tabashnik et al. 2013). The integration of two or more toxic genes with other control tactics may further slow increases in resistance.

4.6.2 Impacts on Non-target Insects

Insects play an important role in the ecosystem and human economy as crop pollinators, natural enemies (predators and parasitoids) and detritivores. Honey bees are the best-known pollinators and often improve fruit and seed yields (Crane and Walker 1984) with the additional advantage of honey production. Cotton nectar is attractive to bees, but they are not required for pollination. It is considered that GM crops may have hazardous effects on bees as well as other insect pollinators. Most studies showed no deleterious effects on pollinators, but facts indicate dose-dependent hazardous effects to bees (Malone and Burgess 2009). Similarly, natural enemies (predators and parasitoids) are significant regulators of insect pests. It is evident that the survival of natural enemies depends on the supply of host insects. So, the reduction in insects feeding on GM crops ultimately affects the natural enemies' population. GM crops could have both direct and indirect effects. Many laboratory studies on Bt cotton demonstrated negative tritrophic impacts on predators (*Orius tristicolor* W. and *Geocoris punctipes* S.) (Ponsard et al. 2002) and parasitoids (*Cotesia marginiventris* C. and *Copidosoma floridanum* A.) (Baur and Boethel

2003). Therefore, the impact of GM crops needs to be investigated carefully to develop insect management techniques with minimum effects on non-target organisms.

There is no doubt that an escalated world population has increased the need for intensified food production which will contribute to environmental degradation. Increased food production, while protecting resources, requires an upturn in the implementation of current management practices as well as rapid development of innovative and sustainable ways to mitigate the agricultural impact on the environment and public health.

5 IPM in Dryland A griculture Systems

To feed the ever-increasing world population, agricultural productivity needs to ensure food security in every agroecosystem especially dryland agriculture, as it constitutes a substantial proportion of the global agricultural system. In addition, conservation of environmental quality and lessening of others threats associated with indispensable agroecosystem services are imperative contemplations for the implementation of IPM in dryland agriculture systems (Tilman et al. 2002; Sandhu et al. 2008; Nash and Hoffmann 2012). Regular, unremitting and continuous monocultivation of crops year after year and the introduction of exotic crops to enhance agricultural productivity in dryland cultivation systems has resulted in the precipitous increase in the incidence/level of pest populations and lead to the establishment of invasive pest species, respectively (Royer and Krenzer 2000; Royer et al. 2007). Agricultural pest management systems still depend on broad-spectrum synthetic pesticides; there is an imperative and imperious need for the strategic implementation of IPM tactics to exploit the practical, theoretical and conceptual IPM principles (Samiee et al. 2009; Nash and Hoffmann 2012). The lack of awareness of the operating manpower of dryland agriculture systems and non-implementation of IPM programs by farmers has lead to an erratic and impulsive outbreak of pests, reduced yields and profit margins, and exclusive dependency on pesticides-based approaches (Royer and Krenzer 2000; Royer et al. 2007; Samiee et al. 2009; Nash and Hoffmann 2012). Different fall-on strategies including landscape modifications, host plant resistance (HPR), ecological indicators, reliable predictors, and emergency intervention should be implemented for the manipulation and stability of crop environments or agroecosystems that would not be conducive for the pest population. Despite such strategies, if a pest population outbreak then an operational approach including broad-spectrum multiple chemical control (fall-off strategies) may be a better option to protect productivity (Nash and Hoffmann 2012). The changing scenario of climatic conditions as well as the increasing demand for quality food emphasizes the use of a dynamic approach of IPM. The techniques should be efficient, cost-effective and sustainable, produce quality yields and the least degrading to environmental quality, biodiversity conservation, mitigation of health hazard effects and low rates of development of ecological backlashes in dryland agroecosystems (Way and van Emden 2000; Samiee et al. 2009). In dryland agriculture systems, such comprehensive and flexible IPM approaches should be practiced and implemented that are highly compatible and a best-fit for changing climatic conditions, agronomic/cultural practices, socio-economic factors and landscape usage. Sustainable and successful implementation of such flexible IPM approaches against pests in dryland agriculture systems depend on a comprehensive understanding of the development of simple indicators for system imbalance, host–plant resistance, pest population dynamics, amplified system intricacy and emergency intervention of fall-off strategies (chemical control) (Nash and Hoffmann 2012).

5.1 Characteristics of Sustainable Pest Management

The basic characteristics of sustainable pest management include (1) application of multiple tactics in a highly-compatible manner; (2) reduction of pest numbers or their effects below some economic injury level; (3) conservation of environmental quality (Knipling 1979; Pedigo and Rice 2009). However, some scientists advocate some additional characteristics including (1) highly selective for pest (target specific); (2) comprehensive for a production system (non-phytotoxic and increase yield); (3) compatible with ecological principles, and (4) tolerant of potentially-harmful species but within economically-acceptable limits. An IPM program and strategy constituting these characteristics/elements guarantee its success, efficiency, sustainability, social and economic acceptability, and environmental appropriateness for any pest management system (Dhaliwal et al. 2006; Buurma 2008; Heong et al. 2008; Pedigo and Rice 2009; Alam 2010; Schowalter 2011). Effective and sustainable IPM strategies are also contingent on economic decision levels which are critical for defining the course of action, guaranteeing practical pesticide application, reducing outrageous economic damage, safeguarding producer profits, and conserving environmental quality in any agriculture system and pest situation (Norris et al. 2002; Dhaliwal et al. 2006; Pedigo and Rice 2009; Jha 2010; Schowalter 2011).

5.2 Basic Principles of Pest Management System

Any sustainable agricultural system is characterized by healthier and more productive production and protection cropping systems which demonstrates the least application of highly toxic synthetic pesticides. Such systems depend on a holistic pest management approach based on some basic principles (Joshi 2006; Dhaliwal et al. 2006; Dhaliwal and Koul 2007; Singh 2008; Pedigo and Rice 2009) including

- Pest avoidance/exclusion (a precautionary step which inhibits entry of any pest insect into any ecosystem or agroecosystem using techniques such as hand-picking, bagging, trapping, physical barriers, screening, physical beating, rope dragging, banding, burning, sieving and winnowing, acausting (noise creation etc.);

- Identification of a pest and its status (identification of pest species and life stage is the principal component of any IPM program and identifies whether or not the pest is dangerous) (Dhaliwal and Koul 2007; Pedigo and Rice 2009;
- Understanding the biology and ecology of the pest;
- Understanding the structure/components of the agroecosystem (Pedigo and Rice 2009; Schowalter 2011);
- Economic decision levels (Pedigo and Rice 2009); 6) pest monitoring and pest scouting (Dhaliwal and Arora 2003);
- Selection of single or set control tactics;
- Goal of pest management program [prevention (keeping a pest from becoming a problem), suppression (reducing pest numbers or damage to an acceptable level) and eradication (destroying an entire pest population) (Pedigo and Rice 2009)];
- Study factors causing failure of pest management strategies (incorrect identification of insect pest species, selection of inappropriate control measures, selection of incompatible control measures, selection of inappropriate application technique, improper timing of application of control measures, excessive application of same tactics, development of resistance in insect pest species against control measures, adverse climatic conditions, use of incorrect dosage of pest control measure); and
- Public awareness, long-term commitment, planning and improvement of the IPM tactic and strategy (Pedigo and Rice 2009; Schowalter 2011).

5.3 *Requirements of Integrated Pest Management*

Integrated pest management (IPM) is a holistic dynamic approach involving integrated and strategic implementation of available efficient, effective and highly-compatible IPM tactics using information regarding pest scouting, pest forecasting, survey and surveillance, economic decision levels, knowledge of technologies, and biological knowledge of the pests for suppressing pest populations below the economic threshold level (ETL), conserving environmental quality and biodiversity, and enhancing positive cost-benefit-ratios (CBR) under the acceptable limits of social barriers. This definition reviews the sound pillars required for the foundation of a successful IPM program or strategy against any pest in any agroecosystem (Dhaliwal and Arora 2003; Pedigo 2003; Dhaliwal et al. 2006; Buurma 2008; Heong et al. 2008; Pedigo and Rice 2009). IPM is a poly-strand approach that is established on some prerequisites including knowledge of the pest management technology, biological, morphological and ecological knowledge of the pests, structural and functional components of the ecosystem and their interactions, landscape and habitat management techniques, and biological control conservation techniques (Sandhu et al. 2008; Nash and Hoffmann 2012).

Knowledge of the technology is one of the pillars of IPM. The knowledge of different features of any technology that ensures its proper and effective implementation include its nature and type, mode of application (aerial, foliar, chemigation, baits, traps etc.), bio/shelf life, equipment required for its application, factors affecting its performance, compatibility with other management tactics, target specific or broad spectrum, mode of action etc. (Pedigo and Rice 2009). This information guarantees the successful and effective implementation of any technology.

The devising and efficient implementation of an IPM approach/strategy against any pest in any agroecosystem/farming system also depends on the morphological, biological and ecological knowledge of the pest species. This knowledge lays the foundation for an effective and economical pest management strategy, eliminates the factors that result in the failure of the IPM program, minimizes operational input-costs, enhances profitability, guarantees conservation of environmental quality/stability, and reduces health hazardous effects for mankind (Knipling 1979; Norris et al. 2002; Pedigo and Rice 2009). The knowledge of pests includes information on the types of habitat and food preferred by the pest, its lifespan, longevity of its incubation period, life stages found, breeding places, season and behavior (dispersal, migratory, immigrant etc.) (Knipling 1979; Norris et al. 2002; Sorby et al. 2005, Dhaliwal et al. 2006; Pedigo and Rice 2009; Alam 2010; Jha 2010) and an understanding of the complex effects of insects and their interactions with other organisms on ecosystem services (Schowalter 2011).

5.4 Advantages and Disadvantages of IPM

Economics, environmental conservation and food security are among the indispensable factors emphasized by the philosophy of an IPM approach. Implementation of conventional insecticides exerts a negative impact on the environment (insecticidal pollution in lithosphere, hydrosphere and atmosphere, residual toxic impact on non-target organisms, biomagnification of persistent toxic residues at trophic levels) which results in ecological backlash (resistance, resurgence and replacement) in pests and hazardous effects on human health (carcinogenic, mutagenic, teratogenic, respiratory, eyes, digestive ailments) (Sarfraz et al. 2005; Gogi et al. 2006; Pedigo and Rice 2009). These issues are flagrantly addressed by the strategic integration of various IPM tactics including biorational and ecofriendly insecticides. An IPM approach contributes to various economic profits and benefits to agricultural producers, the environment, pest management professionals and organizations, and the general public. Implementation of an integration of insecticide-free IPM tactics and/or calendar-based application of ecofriendly biorational insecticides when required and at lower application rates can reduce pesticide costs by 30–40 %, enhance the acceptability and marketability of the produce at comparatively higher marketable rates. In addition, it will diminish the probabilities of environmental pollution and health issues in the workforce, and increase the knowledge of pest biology and specific pest management techniques and options used in IPM (Olsen 1997; Cartwright et al. 1989; Collins et al. 1992). The following are details of the advantages and disadvantages of an IPM approach practiced in any farming system.

5.4.1 Advantages

- Reduces the possibility of litho-, hydro- and atmospheric contamination with toxic chemical compounds
- Promotes sound structures and healthy plants
- Guarantees protection and conservation of non-target species through reduced impact of IPM activities
- Encourages sustainable bio-based pest management alternatives
- Reduces environmental risk associated with pest management by encouraging the adoption of more ecologically-sound control tactics
- Diminishes the need for and reliability on pesticides by using several pest management options and methods
- Reduces or abolishes issues of pesticide toxic and lethal residues (MRLs) in consumable plant parts, drinking water and other consumable commodities, and ensures food security and residue-free acceptable and marketable produce in national and international markets
- Reduces or eliminates re-entry interval restrictions
- Reduces the chance of exposure to pesticides by workers, tenants, the public and other stakeholders through direct contact, inhalation, oral, food-chain, etc.
- Assuages and moderates public concern about pest and pesticide-related practices
- Guarantees the maintenance or escalation of cost-effectiveness/cost-benefit-ratio in pest management programs
- In the case of export commodities, removes the issue of MRLs as a barrier of export and consignment are accepted in international markets at high values that would be a source of foreign exchange earnings
- Reduces the chance of developing resistance, resurgence and replacement of pest insects (Dhaliwal et al. 2006; Pedigo and Rice 2009).

5.4.2 Disadvantages

- A successful and sustainable implementation of any IPM program in any farming system requires comprehensive planning which is mostly beyond the capacity of illiterate or less-literate farming communities
- IPM requires more resources as alternatives to pesticides
- Cost-effective implementation of IPM on a sustainable basis requires a more comprehensive knowledge of the pest, pest management techniques, agroecosys-

tems and the types and nature of interactions among the various biotic and abiotic components of ecosystems

- IPM requires the development of economic decision-making tools for the economical application of ecofriendly, biorational and bio-based insecticides (Dhaliwal et al. 2006; Pedigo and Rice 2009).

5.5 *IPM Approaches for Enhancing Productivity and Food Security*

In dryland farming systems, monocultures or rotated cultivation supports the ephemeral nature of a pest's food resources (host plants) that directly curtails the performance of natural enemies, pollinators and other beneficial insect fauna and indirectly reduces the density of beneficial fauna and crop yields from high pest pressure (Vandermeer 1989; Booij and Noorlander 1992; Way 1988; Ahern and Brewer 2002; Brewer and Elliott 2004; Tscharntke et al. 2005; Clough et al. 2007). In dryland cropping systems, IPM tactics are used in different ways including incorporation into the cropping system, application for near-term future problems and implementation for currently-active problems. Host plant resistance, biological control (importation, release and conservation methods) and cultural control practices including crop rotation, intercropping, relay/trap cropping, planting density, clean cultivation (pest-free materials), sowing time, harvesting time, tillage, sanitation, adjacent land use, fertilizer application management and irrigation management are generally incorporated into cropping system design in dryland farming systems. Pesticides, biological control by augmentation and tillage practices are generally applied while intercropping, cover cropping, sowing and harvesting times, sanitation, soil fertility and irrigation management are occasionally applied for currently-active problems in dryland farming systems. Biological control (BC) by importation and release for future and current problems, by augmentation in cropping system design or for currently-active problems, and cultural practices like crop rotation, plant population/density, pest-free planting materials and field size are not applied for currently-active problems in dryland farming systems (Holtzer et al. 1996). IPM tactics can be categorized into host plant resistance, biological, mechanical, physical, cultural, genetic and chemical control.

5.5.1 Economic Decision Levels

Effective and sustainable insect pest management depends on economic decision levels (EDLs) which are indispensable for determining the course of action, ensuring sensible pesticide application, reducing ludicrous economic damage, safeguarding producer profits, and conserving environmental quality in any pest situation (Dhaliwal et al. 2006; Pedigo and Rice 2009; Alam 2010; Jha 2010). EDLs were developed in the 1950s by entomologists to determine whether the use of insecticides was appropriate and economical. EDLs are also used to determine if other IPM control tactics like HRP, biological, mechanical, physical, cultural and ecological control processes successfully suppress pest populations or fail to reduce it below a tolerable level. If EDLs manifest the failure of other IPM tactics by suppressing pest populations below tolerable levels, then the use of chemical control becomes mandatory to keep the pest population from reaching the economic injury level. EDLs also determine if any active insect pest problems are prevailing in the cropping system which are defined by pest-scouting techniques (Holtzer et al. 1996; Dhaliwal et al. 2006; Pedigo and Rice 2009). The implementation and utilization of EDLs ensures that the deliberate and sensible use of insecticides helps to avoid the indiscriminate use of insecticides, decreases the intensity of insecticide use, increases the producer profit ratio, conserves natural biodiversity and environment quality, provides solutions for some problems like ecological backlash (resistance, resurgence and replacement), health hazard effects, pesticide residues and the negative impacts on non-target organisms. These EDLs include economic injury level, economic threshold level, gain threshold and damage boundary (Knipling 1979; Pedigo and Rice 2009). The decision to implement any of these EDLs is determined using four principles/rules: No-Threshold-Rule, Nominal-Threshold-Rule, Simple-Threshold-Rule and Comprehensive-Threshold-Rule (Knipling 1979) (see Table 3). The development of precise EDLs for specific pests in particular crops is accomplished with years of research and field experiments carried out under controlled biological, economical, agronomic and environmental conditions to predetermine

Table 3 EDL rules and criteria for their selection and application in pest management program

EDL rules	Criteria for application
No-Threshold-Rule	(i) Pest sampling cannot be done economically
	(ii) Practical response to cure a problem cannot be implemented in a timely manner
	(iii) Once detected, the problem cannot be cured
	(iv) ETL is immeasurably low (some quality losses, disease transmission, rapid growth potential)
	(v) Populations are intense with a general level of density always above EIL
Nominal-Threshold-Rule	Based on the experiences and expertise of the entomologist and most frequently used in a pest management program.
Simple-Threshold-Rule	Implies the use of calculated ETLs which are based on market values, management costs, damage done per insect, yield reduction per plant, and the amount of damage avoided.
Comprehensive-Threshold-Rule	Based on interactive effects of biotic and abiotic factors on plant stresses and can be calculated and implemented only if the computer-based information delivery system and acquisition of on-farm computers are ensured.

Knipling (1979)

pest density. EDLs vary with cultivar, growing location, pest-damaging stage, etc. (Holtzer et al. 1996). Along with EDLs, some essential and indispensable additional information (such as resistance, susceptible or tolerance potential, growth stage, yield potential of crop, status and impact of naturally-occurring biocontrol agents, status of other factors such as soil moisture, soil fertility, crop residues etc., and their impact on pest biology and damage potential) are prerequisites and should be obtained for the economical application of insecticides (Knipling 1979; Holtzer et al. 1996; Pedigo and Rice 2009).

5.5.2 Insect Pest Monitoring System

Monitoring and forecasting a pest's resistance, resurgence, replacement and outbreak have reached a crucial and decisive position and the attention of pest management scientists (Maelzer and Zalucki 2000). The prediction of pest population dynamics and its outbreak is determined by understanding the life-history strategies of key pests, including the biotic potential, reproductive and survival potential, mode/rates of reproduction, migratory, trivial and dispersal behavior, diapause, and the growth pattern (r-strategic, k-strategic and a-strategic) of pests (Birch 1948; Greenslade 1983). The implementation of EDLs in a pest management program for crop pests in dryland systems should be emphasized for economical pest suppression. However, EDLs as decision-making tools in dryland pest management require the establishment of ETLs. Farmers should exploit the additional information on monitoring and scouting techniques to determine and implement EDLs in dryland cropping management systems. In such systems, advanced technologies including global positioning system (GPS), remote sensing technology and global information system (GSI) not only make the monitoring and EDL system more effective/efficient but can lay the foundation of precision agriculture. Using these advanced technologies would reduce the costs involved in acquiring pests, host plants, beneficial fauna and soil-related information (pest stage, damage intensity, crop growth stage, soil condition, water requirements, etc.). These technologies would also ensure precise site-specific application of nutrients (fertilizers) for good crop health and pesticides for economical management of pests (insect, weeds, pathogens, etc.) in dryland farming systems. Data maps developed using these technologies will help to detect the precise spatial presence and location of insect pests on crops, and GPS units mounted with pesticide application equipment would help to apply a precise quantity of the pesticides (Holtzer et al. 1996).

5.5.3 Host Plant Resistance (HPR)

In dryland farming systems, HPR is the most commonly-exploited IPM tactic in which resistant cultivars are incorporated into cropping system design. However, HPR may be selected by the farmers in dryland cropping systems if the chances of pest outbreaks are certain during the cropping season (Holtzer et al. 1996). HPR is ecofriendly, easy and simple to apply and targets specific pest management techniques with improved yield potential. It has been practiced widely in dryland and marginal cropping systems (Park et al. 2006; Ortiz et al. 2007; Hillocks 2009). GM crops with toxin-transcribing genes confer resistance to many Lepidopterous, Dipterous, Coleopterous and Hemipterous insects and reduce the application intensity of persistent and lethal pesticides (Cattaneo et al. 2006; Zalucki et al. 2009). HPR technology will guarantee the stability of dryland agroecosystems, but single strategy resistance HPR-techniques may jeopardize ecosystem biodiversity due to the homogenization of the landscape and lead to secondary pest resurgence and replacement (Altieri et al. 2004; Gu et al. 2008; Wang et al. 2008; Hillocks 2009). HPR technology will be effective and acceptable in dryland farming systems if it: (1) demonstrates resistance against the insect pest complex and weeds (multiple pest resistance gene systems); (2) reduces the rate of development of ecological backlash (resistance, resurgence and replacement) in insect pests; (3) eliminates the requirement of chemical control for the pest complex; (4) ameliorates the performance of natural enemies in the system; (5) does not deteriorate yield potential; and (6) does not hamper with anti-herbivory allelochemicals and phyto-allexins synthesis pathways of plants (Glamoustaris and Mithen 1995; Harrington et al. 1998; Horne and Page 2008).

5.5.4 Crop Rotation System

Any modification to the crop rotation system will exert a profound and reflective influence on the agroecosystem, agricultural landscape, interaction and functioning of habitat components, cropping system, biotic potential of pests, performance and activities of natural enemies, soil fertility and intensity of pest problems (Ahern and Brewer 2002; Elliott et al. 2002). Crop rotation systems in dryland areas can also enhance water-use efficiency and confirm the stability or increase in farm profits (Peterson et al. 1996). Growers practicing crop rotations need more frequent insect pest monitoring than those growers who do not. Other than insect pest control, crop rotations benefit dryland growers by impacting weed management, enhancing labor and equipment efficiency, and promoting resistance in crops to insect pests. This rotational system should use cultivars which exhibit potential for resistance to insects and other pests, fewer yield losses and high-yielding potential (Koul and Cuperus 2007).

5.5.5 Ecological Engineering of the Landscape

Ecological engineering of the dryland agricultural landscape ensures an increase in biodiversity, conservation of beneficial fauna and suppression of insect pests as its foremost consequences (Gurr et al. 2004; Schellhorn et al. 2008). Habitat modification will change the composition of the arthropod community, alter pest–parasitoid/pest–predator interactions, promote conservation and augmentation of natural enemies, and ultimately impact the efficacy of any IPM system (Tilman and Knops 1997; Harwood et al. 2009). However, implementation of this strategy will be difficult and intricate in dryland cropping systems on a large scale or including the surrounding landscape such as pasture cropping (Jones 1999; Schellhorn et al. 2008). Undisturbed strips of grassy non-crop intercropped with major crops will provide a habitat conducive to the multiplication of natural enemies and enhance pest control in the crop (Collins et al. 2003; Macleod et al. 2004; Tsitsilas et al. 2011).

5.5.6 Conservation Biological Control

Biological control describes the exploitation of predators, parasites and pathogens for pest control. It is considered ecofriendly, self-perpetuating once established, environmentally safe, target specific and best-fit in an IPM program (Dhaliwal and Arora 2003; Pedigo 2003; van Emden 2003; Dhaliwal and Koul 2007; Jonsson et al. 2008; Pedigo and Rice 2009). It plays an indispensable role in controlling insect pests in economic crops, fruit orchards, vegetables, ornamental plants and fodder/pasture in any cropping system. Dryland cropping systems need to: (1) recognize the values of natural enemies at the farm level; (2) investigate their effectiveness and abundance in different dryland zones and prevailing seasons; (3) explore the limiting biotic/abiotic factors involved in the failure of a biocontrol system; (4) determine and standardize the techniques for the collection, mass propagation, release and conservation of indigenous biocontrol natural enemies, and (5) import and manipulate exotic natural enemies (van Emden 2003; Jonsson et al. 2008). The abundance and performance of natural enemies in any cropping system are regulated by the conservation of floral diversity, modification and manipulation of habitat, maintenance of diversity outside and/or inside the major crop fields planned for biological control, integration and implementation of IPM tactics highly conducive and compatible with biological control, and conservation of the natural enemies/pest ratio through manipulation and augmentation techniques (van Emden 2003; Jonsson et al. 2008). Habitat modification with diversified flowering species or artificial diets supports the abundance and performance of natural enemies, specifically parasitoids. The female parasitoid, *Pimpla examinator* (F.) of the pine shoot moth, *Rhyacionia buoliana* (S.) is not attracted to pine oil fragrance until the female has fed on floral nectar to mature the eggs. Once the female parasitoid has fed and matured the eggs, the female is attracted to the pine oil smell and locates the host moth (Thorpe and Caudle 1938; van Emden 2003; Jonsson et al. 2008). Sometimes, parasitizing and predatory stage(s) of parasitoids and predators, respectively, do not synchronize with the host/prey stage or food is scarce (for host or prey). In these conditions, the provision of obligatory or other alternate host/prey guarantees the conservation of natural enemies (Hardy 1938; van Emden 2003; Jonsson et al. 2008). For example, emergence of the larval parasitoid (*Diadegma fenestralis* H.) of the diamondback moth (*Plutella xylostella* L.) in autumn does not synchronize with the presence of larval stages of the host (available in autumn in pupal stages) and they must, therefore, survive on another host (*Crataegus monogyna* J.) (Hardy 1938; Van Emden 2003). The appearance and outbreak of *Ichneumon dispar* (P.), a parasitoid species of gypsy moth (*Lymantria dispar* L.), occurs when the preferred host is scarce in the forest, but they survive on 45 caterpillar species as alternate hosts (Babaei et al. 2009). Habitat modification also involves practices that make the microclimate highly conducive to the conservation and performance of natural enemies in the cropping system. Taylor (1940) documented that maintaining a conducive microclimate, specifically humidity and temperature, in an abandoned coffee plantation by shading enhanced the abundance and performance of natural enemies which ultimately suppressed antestia bugs (*Antestiopsis* spp.). Conservation of biological control can be accomplished by maintaining diversity outside or inside the cropland by establishing insects/natural-enemies-banks (INEB) or biological-control-conservation-strips (BCCS). An INEB or BCCS system can be established by growing grass/hedgerows/flowering/nectar-plantations banks around the farmland, along roadsides, in the periphery of farmlands and/or stripped cultivation of alternate/trapping plantations in cultivated crops. Such practices/systems can accommodate and accumulate overwintering predators/parasitoids and provide a conducive environment for nectar feeding by the predacious adults of predators (Chrysopids, syrphidflies etc.) and adults of parasitoids. These also help to increase and maintain the natural enemy to pest ratio and enhance the chances of conservation of biological control (Doutt and Nakata 1973; Sotherton 1984; Thomas and Wratten 1988; Boller 1992; Gurr et al. 1998; Murphy et al. 1998; Powell 2000; Van Emden 2003; Jonsson et al. 2008). Growers prefer to exploit insecticides due their knockdown effects and quick control of pests to discourage weeds on their farmland. They are not acquainted with the concepts, complexity and practices of biodiversity conservation and management. It is, therefore, imperative to arrange outreach programs and campaigns at farmers' door steps or through media and distance-learning/online training sessions to create awareness on the implementation and conservation of biological control in dryland cropping systems.

Growers cannot avoid chemical pest control that interrupts the conservation of biological control in any cropping system. The conservation of biological agents in pesticide regimes is a different approach from the concept of conservation biological control by habitat modification. This former approach (conservation of biological control in pesticide regimes) focuses on using selective, ecofriendly and biorational insecticides/approaches suxh as IGRs, Bt crops (GM crops), botanicals, microbial insecticides, spynosins, avermectins, allellochemical, pheromones and plant-incorporated products/poisons (PIP). Conservation of natural enemies in pesticide regimes can also be achieved by modifying pesticide application techniques (seed dressing, chemigation, whorl-application etc.) and applying pesticides at safe pre- or post-application intervals (Morse 1989; van Emden and Peakall 1996; Van Emden 2003; Dhaliwal et al. 2006; Jonsson et al. 2008; Pedigo and Rice 2009).

5.5.7 Biorational and Other Innovative Approaches

'Biorational control' involves using chemicals that suppress insect populations by modifying their behavior, disrupting growth and impeding reproduction. Generally and operationally, biorational pest management involves substances or processes that execute diminutive or no adverse consequences to the environment and non-target organisms (humans, beneficial fauna and flora etc.); but they impose lethal, suppressive or behavior-modifying effects on a target organism and augment the specific control system (Pathak and Dhaliwal 1986; Dhaliwal and Arora 2003). Historically, Carl Djerassi used the term 'biorationals' for the first time for pheromones, insect hormones and hormone antagonists (Dhaliwal and Arora 2003). However, he did not propose any particular definition of biorationals but described their properties such as species specificity, active lethality at low concentrations and low persistency, and toxicity to non-target vertebrates (Djerassi et al. 1974). Biorational approaches include the strategic application of insect growth regulators (IGRs) and semiochemicals (pheromones and allelochemicals) while other innovative approaches include the use of propesticides, light-activated pesticides, avermectins, spinosyns, etc. Insect growth based insecticides include IGRs that interfere with cuticle formation mechanisms (e.g., chitin synthesis and degradation inhibitors, cuticle sclerotization disrupters, etc.) and with the secretion and actions of insect growth hormones (e.g., brain hormones, juvenile hormones, molting hormones, etc.). These are used as foliar sprays on crops to protect them from the attack of both chewing and sucking type insect pests. However, they do not affect the health of human beings (Altstein et al. 2000; Ishaaya 2001; Dhaliwal and Arora 2003; Pedigo 2003; Horowitz and Ishaaya 2004; Dhaliwal et al. 2006). Pheromones are the chemicals that induce any chemical communication between similar species. There are different types including sex, aggregation, alarm, trail and host-marking pheromones (Tschinkel and Close 1973; Verheggen et al. 2010; Heuskin et al. 2011; Chapman 2013) which are used to develop monitoring, male disruption or confusing/decoy, mass trapping and attract-and-kill techniques (Dhaliwal and Arora 2003; Pedigo 2003; Horowitz and Ishaaya 2004; Dhaliwal et al. 2006; Witzgall et al. 2010) (Table 4). Allelochemicals are interspecific semiochemicals which elicit chemical-signal-based communication in some members of different species. Allelochemicals include repellent, attractants, antifeedants and a large group of other compounds/molecules that regulate interspecific behaviors. These phytochemicals induce antixenotic (antifeedant, repellent, anti-oviposition and adverse behavioral effects) and antibiotic effects (growth, development, survival) in insects. They constitute a variety of plant secondary metabolites such as unusual amino acids, sugars, alkaloids, terpenoids, flavonoids, polyacetylenes, etc. (Dhaliwal and Arora 2003; Pedigo 2003; Dhaliwal et al. 2006), and may be of plant (botanicals, phytoalaxins, allomones etc.) or animal origin. The allelochemicals produced by natural enemies such as predators, parasitoids and pathogens are important in pest management programs. For example, delta-endotoxin produced by *Bacillus thuringiensis* is lethal against many Lepidopterous and Coleopterous insects (Dhaliwal and Arora 2003). They are categorized into allomones, kairomones and synomones.

Table 4 List of biorational and innovative insecticides for ecofriendly and sustainable management of insect pests in dryland ecosystems

Categories	Chemical molecules/compounds	Category/type/example of target insect pests of dry ecosystem	Mode of action	References
Biorational insecticides				
Brain hormone (BH)	Proctolin	Insect pest complex	Disrupt calcium influx	Dhaliwal et al. (2006)
Juvenile hormone (JH)	JH-0, JH-I, JH-II, JH-III, JH-B3 and methyl farnesoate	Insect pest complex	Ecdysis disruption	Bowers et al. (1965)
Chitin sysnthesis inhibitor (CSIs)	Diflubenzuron, chlorfluazuron, teflubenzuron, buprofezin, plumbagin	Sucking and chewing insect pest	Ovicidal, chemosterilant activities, molting disruption	Dhaliwal et al. (2006)
Molting hormones (MH)	ecdysone (20-hydroxyecdysone, 26-hydroxyecdysone, 20, 26-dihydroxyecdysone), ecdysteroids and ecdysterone (makisterone-A, 20-deoxymakisterone)	Sucking and chewing insect pest	Disrupt molting, growth and maturation of insects	Dhaliwal et al. (2006)
Sclerotization disruptors	MON-0585 (ditertiary butyl alcohol), DD	Dipteran, Lepidopterans and Coleopterans	Disrupt the metabolism and deposition of phenolic compounds, proteins and other compounds required for cuticular stabilization	Dhaliwal et al. (2006)
Pheromones				
Sex pheromones	Dodecatrienol, dodecadienol, neocembrene, trilinolein, decadienal, dodecanal	Termites	Male attractant	Costa-Leonardo et al. (2009)

	(E,Z,Z)- and (E,E,Z)-4,6,10-hexadecatrienyl acetates	cocoa pod borer, *Conopomorpha cramerella* S. (Lepidoptera: Gracillariidae)	Male attractant	Zhang et al. (2008)
	Alcohol and acetate molecules	Most moth species	Male attractant	Butler and McDonough (1979, 1981)
	(8*E*,10*E*)-tetradecadien-1-ol, and the corresponding aldehyde, acetate and formate ester	Lepidopteran insects	Male attractant	Van-der-Kraan and Ebbers (1990)
	Hexanal, heptanal, octanal, decanal, undecanol and 6,10,14-trimethylpentadecanon-2	Greater wax moth, *Galleria mellonella* L. (Lepidoptera: Pyralidae)	Male attractant	Lebedeva et al. (2002)
	(2Z, 6E)-7-methyl-3-propyl-2,6-decadien-1-ol., blend of *E-8, E*-10-dodecadien-1-ol and *E*-9-dodecen-1-ol and saturated alcohols of 10 to 18 carbons	Codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae)	Male attractant	Arn et al. (1985)
	(E)-11-tetradecenyl acetate (E11-14Ac); (E,E)-9,11-tetradecadienyl acetate (E9E11-14Ac); (E)-11-tetradecen-1-ol (E11-14OH); tetradecyl acetate; hexadecanal; (E)-11-hexadecenyl acetate (E11-16Ac), hexadecyl acetate; octadecanal; and octadecyl acetate	Lightbrown apple moth, *Epiphyas postvittana* W. (Lepidoptera: Tortricidae)	Male attractant	El-Sayed et al. (2011)
	(2S,3R,7R)-isomers of the propionates of 3,7-dimethyl-2-tridecanol; 3,7-dimethyl-2-tetradecanol; 3,7-dimethyl-2-pentadecanol	Sawfly, *Gilpinia pallida* K.	Male attractant	Hedenström et al. (2006)

(continued)

Table 4 (continued)

Categories	Chemical molecules/compounds	Category/type/example of target insect pests of dry ecosystem	Mode of action	References
	cis and trans forms of propylure (10-propyl-trans-5,9-tridecadienyl acetate)	Pink bollworm, *Pectinophora gossypiella* S.	Male attractant	Jacobson (1969)
	(Z)-11-hexadecenal, (Z)-9-hexadecenal, (Z)-11-hexadecen-1-ol and hexadecanal	Striped rice stem borer, *Chilo suppressalis* W. and yellow stem borer, *Scirpophaga incertulas* W.	Male attractant	Cork et al. (1985)
	(Z)11-hexadecenal/(Z)9-hexadecenal/(Z)7-hexadecenal (Z11-16:Ald)	*Helicoverpa zea* B.	Male attractant	Lopez et al. (1991)
	(Z)-11-hexadecenal 90–99 % + (Z)-9-hexadecenal 10–1 %	*Helicoverpa armigera* H.	Male attractant	Zhang et al. (2012)
	Phenyl propanoids	Most fruit flies	Male attractant	
	Trimedlure [t-Butyl-2-methyl-4--chlorocyclohexanecarboxylate]	Mediterranean fruit fly, *Ceratitis capitate* W.	Male attractant	Beroza et al. (1961)
	Cuelure[4-(p-acetoxyphenyl)-2-butanone]	Melon fly, *Dacus cucurbitae*	Male attractant	
	Methyl eugenol (ME) (4-allyl-1, 2-dimethoxybenzene-carboxylate) and raspberry ketone (RK) (4-(p-hydroxyphenyl)-2-butanone)	Most fruit flies	Male attractant	Vargas et al. (2010)

Other innovative insecticides				
Light-activated insecticides/phototoxins	Furanocoumarines, alpha-terthienyl, polyecetyle, photooxidative dyes (compound of halogenated fluorescein series)	Mosquitoes, beetles, weevils, house flies	Inhibition of feeding, development of larval–pupal intermediates, failure to extricate from pupal case, deformed wings, reduced fecundity, reduced egg viability, direct mortality	Heitz and Downum (1987)
Propesticides	Carbosulfan, acephate, thiodicarb, cartap	Most sucking and chewing insects	Non-toxic in their actual form but highly toxic when metabolized inside the system of insects. Both contact and systemic, neuromuscular blocking agents, inhibition of synaptic transmission	Dhaliwal et al. (2006)
Avermectins (macrocyclic lactones)	Abamectin, ivermectin, selamectin, doramectin	Mites, insect pests	Acaricidal and insecticidal action, disrupt the action of both ligandated/glutamate-gated (GABA) and voltage-gated chloride channel causing an influx of chloride ions into the cells, leading to hyperpolarisation and subsequent paralysis	Dhaliwal et al. (2006)
Milbemycins (macrocyclic lactones)	Milbemycin	Mites and insect pests	Same as for avermectin	Lasota and Dybas (1990)
Spinosyns	Spinosad (mixture of spynosyn-A & D), spintoram	Coleopteran, Dipterans, Lepidopteran, Thysanoptrans	Contact and stomach poison; disruption of nicotinic acetylcholine receptors	Herbert (2010)

Their application in a pest management program of any cropping system not only guarantees environmental safety, and conservation of biodiversity, biological control and environmental quality but also highly supports the philosophy of IPM approaches (Dhaliwal and Arora 2003; Pedigo 2003; Dhaliwal et al. 2006).

6 Conclusions and Future Research Thrusts

The growing population, overuse, pollution, tidal surges and competing interests are degrading water resources globally. This will increase the area of dryland regions in the coming decades. Therefore, enhancing crop productivity in agroecosystems particularly in dryland areas is essential to feed the future population. Insect pests in dryland agroecosystems will be a major threat to crop production as they modify themselves according to environmental conditions. Sustainable agriculture in dryland areas should be practiced by integrating modern, research-proven technologies that are simple, cheap, easy-to-use and compatible with the respective regions. Climate variability and change have become the main reasons for the increased frequency of drought and its effect on crop planting times, growing season lengths, shifts in crop type or cultivars, pest incidence and crop productivity. Climate change, especially dry conditions, will affect the life-history traits of hosts and natural enemies differently. These effects might be more noticeable on natural enemies as they are at a higher trophic level. A better understanding of the behavioral, physiological and functional adaptations of natural enemies to climate extremes, both at the species and community level, will maximize the extent of natural regulation of insect pests, particularly in dryland areas.

Other IPM options including cultural, mechanical, biorational, genetic and biotechnological approaches with chemical control as a last resort should be tailored to water-stressed conditions. Dryland systems are not in equilibrium, having multiple thresholds and a diverse agricultural landscape, and often exhibit multiple ecological and social ranks. Hence, the extrapolation of laboratory experiments and field-simulating data, especially as they apply to arid environments, must be made with reservation. In dryland cropping systems, multidimensional and multidisciplinary research approaches, scientific/scientists and expert collaboration in long-term and large-scale projects should be executed to tackle/solve the prevailing and emerging plant production and protection issues.

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